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Preliminary Framework for Uncertainty Quantification and Propagation of the Fission Surface Power System Mass Estimates

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Preliminary Framework for Uncertainty Quantification and Propagation of the Fission Surface Power System Mass Estimates

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Abstract

Estimating the mass of the Fission Surface Power (FSP) system is crucial to the success of integrating FSP into a Moon or Mars human mission architecture. Past and current estimates of the FSP system have been made using the EZ FSP Sizer tool, which is a nuclear power system sizing tool developed at NASA Glenn Research Center. The tool currently applies a 20% mass growth allowance to mass estimates. The purpose of this report is to introduce a preliminary framework that quantifies and propagates the uncertainty of FSP mass estimates produced using the *EZ FSP Sizer* tool, providing a method to produce probabilistic mass estimates of an FSP system. This work can augment the capabilities of the *EZ FSP Sizer tool* and lay a foundation to aid with future decision making. Sensitivity analyses were performed on parameters that were used to model probability distributions of FSP subsystem masses. Results point to the need of reducing mass estimate uncertainty through hardware development and empirical validation. Although the modeled uncertainties are first order, they can be useful for informing when and how mass estimates can be used reliably.

1.0 Introduction

Literature has indicated that Fission Surface Power (FSP) system masses are estimated to be on the order of metric tons for systems providing electrical power output on the order of kilowatts (Refs. 1 to 3). Crucial to the success of integrating FSP into a Moon or Mars mission architecture is providing accurate estimates of the FSP system mass. Underestimating the FSP system mass can have detrimental cascading impacts on many critical aspects of mission planning such as launch vehicle and lander performance requirements, surface and deployment logistics, and surface power strategy trades.

System mass growth from the design phase to completion can occur due to many factors including changing requirements and constraints, system performance uncertainty, and integration complexities, which are issues that the FSP system will face. As a result, providing accurate mass estimates of a system in the early phases of a mission (prior to the existence of representative hardware) is a challenging task. While mass growth allowance standards exist, Thompson et al., indicated that "30% of historical programs experience inert mass growth in excess of the allowable growth and margin recommended level of 32.5%" (Ref. 4).

Past and current mass estimates for the FSP system have been made using the *EZ FSP Sizer* tool, which is spreadsheet based nuclear power system sizing tool developed at Glenn Research Center (Ref. 1). The *EZ FSP* Sizer tool was developed during the Prometheus program to support the Jupiter Icy Moons Orbiter (JIMO) power system analysis and updated to support the Constellation-era FSP studies (Ref. 1). The *EZ FSP Sizer* tool can provide mass estimates for the different subsystems associated with FSP including: the reactor, shield, power conversion, heat rejection, power management and distribution (PMAD), and utility

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interface pallet. Further details on *EZ FSP Sizer* capabilities can be found in Reference 1. The current government reference design (GRD) of the FSP system reports the mass estimate using the *EZ FSP Sizer* tool with 20% mass growth allowance margin.

The purpose of this report is to introduce a preliminary framework that quantifies and propagates the uncertainty of FSP mass estimates produced using the *EZ FSP Sizer* tool, providing a framework to generate a probabilistic model of FSP mass estimates. This effort can augment the capabilities of the *EZ FSP Sizer tool* and help lay the foundation for providing preliminary results that could be helpful for decision making.

2.0 Methodology

The high-level approach to quantifying the FSP mass uncertainty involves three key steps:

1. Generate a metric that captures the Technology Readiness Level (TRL) and Advanced Degree of Difficulty (AD^2) of the subsystems within the FSP system.
2. Use the metric from (1) to generate a probability density function for mass growth margin.
3. Perform a Monte Carlo analysis: sample mass growth margin to generate the average and variance of the mass of each subsystem. Then, calculate the average total mass and standard deviation of the total FSP system.

Further details related to each step are explained in detail in the following sections.

2.1 TRL and AD^2 Metric

In 2024, the FSP team released a Technology Maturation Plan (TMP) that provides the Technology Readiness Level (TRL) and Advanced Degree of Difficulty (AD^2) of the subsystems and components within the FSP system (Ref. 5). The goal of this step was to generate a metric γ that captures both the TRL and AD^2 as a proxy indicator of mass growth margin of a subsystem. Equation (1) defines the mass growth margin metric γ where n represents the number of components in the subsystem. Note that TRL and AD^2 both range from 1 to 9, explaining why γ includes the expression $(9 - TRL)$ and $9 \times 2\ \times n$.

$$\gamma = \frac{\sum_1^n (9 - TRL) + (AD^2)}{9 \times 2\ \times n} \tag{1}$$

Lower γ corresponds to higher TRL and lower AD^2 , while higher γ corresponds to lower TRL and higher AD^2. The γ metric for each FSP subsystem is summarized in Table I.

TABLE I.—γ FOR EACH FSP SUBSYSTEM

FSP Subsystem	γ
Reactor Core (RC)	0.361
Shield (S)	0.361
Power Conversion (Brayton) (PCS)	[a]0.556
Power Conversion (Stirling) (PCS)	[a]0.278
Heat Rejection (HR)	0.236
PMAD (PMAD)	0.429
User Interface Pallet (UI)	[b]0.556

[a]Note that for the Brayton and Stirling power conversion subsystem, the γ values were calculated using the "Overall Stirling" and "Overall Closed Brayton" entries for TRL and AD^2 in Reference 5.
[b]The user interface pallet TRL and AD^2 values were estimated by the author.

2.2 Mass Growth Margin Probability Density Function

A Beta distribution was selected to represent the probability density function or “degree of belief” of the mass growth margin. The Beta distribution is parametrized by two positive “shape” parameters α and β, which control the shape of the distribution. The mean (μ) and variance (σ^2) of the Beta distribution modeled by Equation (2).

$$\mu = \frac{\alpha}{\alpha + \beta} \qquad \sigma^2 = \frac{\alpha\beta}{(\alpha + b)^2(\alpha + \beta + 1)} \tag{2}$$

The Beta distribution was selected for the follow reasons:

1. The range of the distribution is over the finite interval [0,1], making it a convenient representation of mass growth margin (%).
2. If α >1 and β>1 and $\alpha < \beta$, the distribution can be shaped to skew to the left. This can be used to represent lower mass growth margin.
3. If α >1 and $\beta > 1$ and $\alpha > \beta$, the distribution can be shaped to skew to the right. This can be used to represent higher mass growth margin.
4. The shape parameters α and β control the variance of the distribution. This can be used to “flatten” the distribution and better represent uncertainty in the mass growth margin.

The parameters used to shape the Beta distribution are documented in Table II.

Examples of what the Beta distribution looks like for different values of α and β can be seen in Figure 1.

TABLE II.—PARAMETERS FOR THE BETA DISTRIBUTION

Parameter	Description
μ	$\mu = \gamma$ γ is a proxy parameter for mean mass growth margin.
a	$\alpha = 10$ This value was selected such that higher μ results in higher variance, which is heuristically consistent with higher γ indicating less confidence in the mass growth margin. A sensitivity analysis associated with varying the values of α are discussed in Section 3.3.
b	$\beta = \alpha\frac{1-\gamma}{\gamma}$ This expression is rearranged from Equation (2), where $\mu = \gamma$

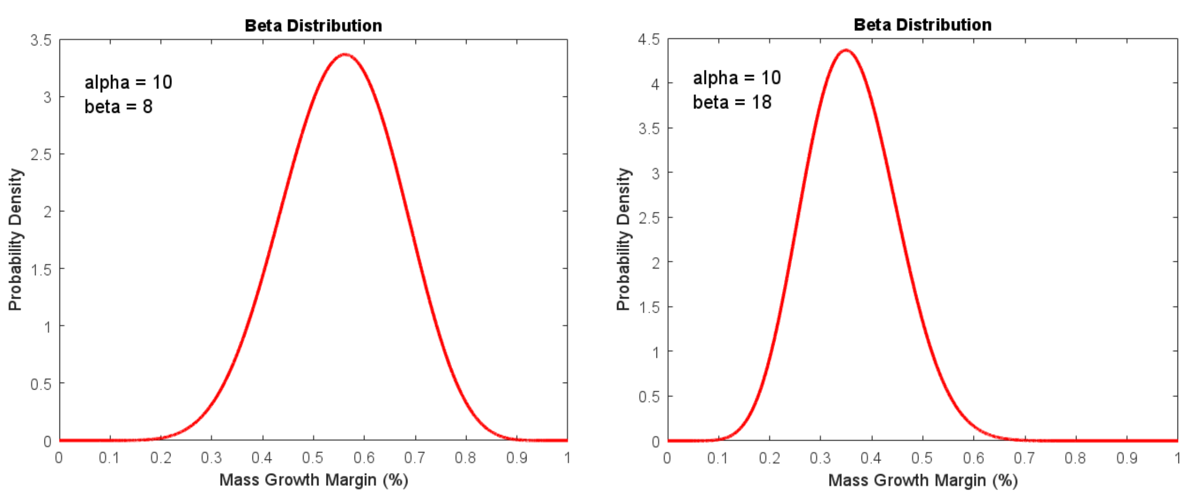

Figure 1.—Example Beta distributions for different shaping parameter.

2.3 Monte Carlo Analysis

Using the generated Beta distributions for each subsystem, each distribution was sampled 10000 times and the average mass and standard deviation of each subsystem and total FSP system was calculated using the Equations (3) to (6). Subscript s denotes a subsystem (reactor core, heat rejection etc…), and subscript i denotes the i^{th} sample of n samples of each subsystem's Beta distribution. m_s is the estimated mass of a subsystem from *EZ FSP Sizer*, $\overline{m_s}$ is the average mass of the subsystem, σ_s is the subsystem mass standard deviation, m_{FSP} is the total FSP mass, $\overline{m_{FSP}}$ is the average FSP total mass, and σ_{FSP} is the FSP mass standard deviation.

$$\overline{m_s} = \frac{1}{n}\sum_{i=1}^{n} m_s(1+\gamma_i) \tag{3}$$

$$\sigma_s = \sqrt{\frac{1}{n-1}\sum_{i}^{n} \left| m_s(1+\gamma_i) - \overline{m_s} \right|} \tag{4}$$

$$\overline{m_{FSP}} = \frac{1}{n}\sum_{i=1}^{n} m_{RC}(1+\gamma_i) + m_S(1+\gamma_i) + m_{PCS}(1+\gamma_i) + m_{HR}(1+\gamma_i) + m_{PMAD}(1+\gamma_i) + m_{UI}(1+\gamma_i) \tag{5}$$

$$\sigma_{FSP} = \sqrt{\frac{1}{n-1}\sum_{i}^{n} \left| m_{FSP_i} - \overline{m_{FSP}} \right|} \tag{6}$$

2.4 Assumptions and Limitations

The key assumptions associated with the methodology are presented in Table III.

TABLE III.—ASSUMPTIONS ASSOCIATED WITH THE METHODOLOGY

Assumption aspect	Description
γ metric	There is an additive relationship between TRL and AD^2 and a proportional causal relationship between γ and mass growth margin (i.e. lower TRL and higher AD^2 causes higher mass, and that γ is an acceptable proxy for mass growth margin). This is generally supported by historical trends in mass growth and engineering heuristics, which makes the assumption reasonable in this preliminary framework.
γ metric	γ was formulated to be a metric normalized between 0 to 1 and is therefore a proxy indicator of mass growth margin (%). This means that the maximum mass growth margin is 100%. This is a reasonable assumption for this preliminary framework.
γ metric	All components listed under the subsystem in the TMP will be used in the subsystem. This provides an overall mass growth margin metric for the subsystem even if not all components will be used in the final system.
Mass growth margin probability density function	The mass growth margin follows the shape of a Beta distribution. This was a judgement based on heuristics.
Sampling mass growth margin	10,000 samples of the mass growth margin for each subsystem is adequate
Sampling mass growth margin	The mass growth margin of each subsystem is independent of each other. In reality, the mass of subsystems is not independent of each other. For example, the cold end temperature of the power conversion system is tightly coupled with radiator size, meaning that the mass of the power conversion subsystem can have an impact on the mass of the heat rejection subsystem. The mass associated with integrating subsystems is also relevant.

TABLE IV.—FSP SYSTEM MASS ESTIMATE COMPARISON WITH THE GRD 40 KWE SYSTEMS

Subsystem [kg]	40 kWe GC-Brayton		40 kWe HP-Stirling	
	GRD Estimate with 20% MGA [kg] (Ref. 1)	Results [kg ± σ]	GRD Estimate with 20% MGA [kg] (Ref. 1)	Results [kg ± σ]
Reactor	1696	1922 ± 126	1358	1540 ± 101
Shield	1800	2041 ± 137	1644	1866 ± 122
Power Conversion	1418	1839 ± 135	1194	1271 ± 72
Heat Rejection	1061	1091 ± 57	841	867 ± 46
PMAD	481	573 ± 40	736	875 ± 62
Utility Interface	1046	1356 ± 98	1046	1357 ± 100
Total	7502	8825 ± 262	6820	7775 ± 214

3.0 Results and Discussion

3.1 Government Reference Design Comparison

A MATLAB script was written to generate and sample the probability distribution functions and compute the total mass and standard deviation of the FSP system. Using the mass estimates of the GRD systems (40 kWe Gas Cooled Brayton and 40 kWe Heat-pipe Stirling) for the outlined methodology, the average total mass, variance, and standard deviations are reported in Table IV (highlighted gray). The GRD mass estimates, with 20% mass growth allowance (MGA), are included for comparison. The code used to generate the results in Table IV can be made available upon request.

Table IV shows that the total FSP mass estimates calculated using the outlined method exceeds that provided by *EZ FSP Sizer*. However, it is important to note that the results are subject to the assumptions outlined in Table III.

3.2 Sensitivity Analysis of γ

The methodology presented in this report is rooted in the TRL and AD^2 values assigned to the components of each subsystem. While documented criterions exist on how to assign TRL and AD^2 values to different components, there is a level of subjectivity inherent in assigning TRL and AD^2 values to different components. Thus, it is prudent to conduct a sensitivity analysis to quantify the impacts of uncertain TRL and AD^2 values to the total FSP mass.

3.3 Central Difference Partial Derivative

Calculating the partial derivative of the average total FSP mass with respect to β for each FSP subsystem can provide valuable insight into how a unit change in γ can impact total FSP system mass. The central difference formula, shown in Equation (7) was used to calculate the partial derivative. $\overline{m_{FSP}}$ is the average FSP total mass, γ_i is the γ metric for an FSP subsystem, $\gamma_{i,0}$ is the baseline γ metric for an FSP subsystem (documented in Table I), and $\Delta\gamma_i$ is selected to be 0.1.

$$\left.\frac{\partial \overline{m_{FSP}}}{\partial \gamma_i}\right|_{\gamma_{i,0}} \approx \cdot \frac{\overline{m_{FSP}}(\gamma_{i,0} + \Delta\beta_i) - \overline{m_{FSP}}(\gamma_{i,0} - \Delta\gamma_i)}{2\Delta\gamma_i} \tag{7}$$

Table V documents the partial derivative of the FSP total mass for the 40 kWe GRD systems with respect to each subsystem's γ metric. The code used to calculate the results can be made available upon request.

TABLE V.—PARTIAL DERIVATIVE OF THE TOTAL FSP MASS WITH RESPECT TO EACH SUBSYSTEM'S γ METRIC

FSP Subsystem γ	Partial derivative of total mass (GC-Brayton) [kg/ γ]	Partial derivative of total mass (HP-Stirling) [kg/ γ]
Reactor Core	1411	1127
Shield	1470	1356
Power Conversion (Brayton)	1189	N/A
Power Conversion (Stirling)	N/A	1016
Heat Rejection	896	727
PMAD	392	640
User Interface Pallet	875	859

3.3.1 Discussion

There are several key insights that can be gleaned from the results in Table V. First, the results indicate that the total FSP mass is most sensitive to the γ value of the shield followed by the reactor core, power conversion, heat rejection, user interface pallet, PMAD. This order is expected, as it follows the order of the most to least heavy subsystem mass provided by *EZ FSP Sizer* for the government reference design. The partial derivative of the total mass with respect to the γ value of each subsystem can be used to calculate the change in total FSP mass for a given change in γ value of each subsystem. For instance, a 10% increase in the γ_{RC}, γ_{S}, γ_{PCS}, γ_{HR}, γ_{PMAD} and γ_{UI} of the 40 kWe GC-Brayton GRD system results in a 141.1 kg, 147 kg, 118.9 kg, 89.6 kg, 39.2 kg, and 87.5 kg increase in the total FSP mass respectively. Collectively, this totals to a ~600 kg (over two times the payload mass to lunar surface of Firefly's Blue Ghost lander (Ref. 6)) increase in mass if the γ value of each subsystem is underestimated by 10%.

This highlights the necessity of reducing uncertainty in mass estimates through hardware development and empirical validation. Given that variations in TRL and AD² values can influence the γ parameter and result in substantial swings in estimated mass, building and testing hardware is essential.

3.4 Sensitivity Analysis of α

The results presented in Table IV are based on each subsystem's mass growth margin distribution having the α shape parameter of 10. The value α = 10 was selected because it mathematically allows the distribution to indicate that higher γ (mean mass growth margin) results in higher variance, which is heuristically consistent with higher mean mass growth margin indicating less confidence in knowing what the true mass growth margin is.

In a Beta distribution, α can be any positive number. However, for the ranges of γ in this analysis (see Table I), values of α ranging from $1 < \alpha <$ ~100 allow the Beta distribution to indicate that higher γ (mean mass growth margin) results in higher variance. Thus, it is important to conduct a sensitivity analysis to understand the impacts of varying α. To do so, the method described in Section 2.0 will be repeated for two values representing the upper and lower bounds of α, 2 and 100. The results are shown in Table VI.

TABLE VI.—FSP SYSTEM MASS ESTIMATES FOR THE GRD 40 kWe SYSTEMS FOR DIFFERENT VALUES OF α

Subsystem	40 kWe GC-Brayton				40 kWe HP-Stirling			
	GRD Estimate with 20% MGA [kg] (Ref. 1)	Results $\alpha = 10$ [kg ± σ]	Results $\alpha = 2$ [kg ± σ]	Results $\alpha = 100$ [kg ± σ]	GRD Estimate with 20% MGA [kg] (Ref. 1)	Results $\alpha = 10$ [kg ± σ]	Results $\alpha = 2$ [kg ± σ]	Results $\alpha = 100$ [kg ± σ]
Reactor	1696	1922 ± 126	1927 ± 267	1924 ± 41	1358	1540 ± 101	1541 ± 212	1541 ± 33
Shield	1800	2041 ± 137	2043 ± 281	2042 ± 43	1644	1866 ± 122	1864 ± 260	1865 ± 39
Power Conversion	1418	1839 ± 135	1839 ± 276	1839 ± 43	1194	1271 ± 72	1270 ± 154	1272 ± 23
Heat Rejection	1061	1091 ± 57	1094 ± 124	1092 ± 18	841	867 ± 46	866 ± 96	866 ± 14
PMAD	481	573 ± 40	572 ± 83	573 ± 13	736	875 ± 62	875 ± 127	876 ± 20
Utility Interface	1046	1356 ± 98	1356 ± 200	1357 ± 32	1046	1357 ± 100	1360 ± 203	1357 ± 32
Total Mass	7502	8825 ± 262	8832 ± 540	8827 ± 82	6820	7775 ± 214	7775 ± 453	7776 ± 69

3.4.1 Discussion

Results shown in Table VI indicate that varying the α shape parameter changes the standard deviation while the average mass remains relatively consistent for all values of α. Higher α results in lower standard deviations while lower α results in higher standard deviation. This illustrates how uncertainty quantification inherently involves a degree of subjectivity, as the definition of error bounds is an attempt to quantify engineering judgement. While this underscores the limitations of the method, the author acknowledges that incorporating error bounds into decision-making is critical, as it provides insight into the potential risk and implications of those decisions. Even if the error bounds are approximate, they can provide insight into how far the mass model might deviate from reality, therefore informing when and how the model can be used reliably.

3.5 Uncertainty Propagation of FSP Mass Estimate

Another output of the uncertainty quantification process is the ability provide a probabilistic model of FSP mass estimates through uncertainty propagation. In other words, providing the probability that the total mass of the FSP system may fall within a particular mass range. This section demonstrates the process of generating a probabilistic mass model for the FSP system and interpreting how the results may produce useful insight for mission planning.

As mentioned in Section 2.3, the mass growth margin Beta distributions for each subsystem were sampled 10,000 times, resulting in a FSP total mass distribution from summing the mass distributions of each subsystem. The total mass distributions for the GRD 40kWe, using the parameter $\alpha = 10$, are shown in Figure 2 and Figure 3, and are fitted with normal gaussian distributions.

The probability, P, of the FSP system total mass (m_{FSP}) exceeding a specified mass x can be approximated using Equation (8). $N(m_{FSP} > x)$ represents the number of FSP system masses that exceed the specified mass x.

$$P(m_{FSP} > x) = \frac{N(m_{FSP} > x)}{10000} \tag{8}$$

To demonstrate the process, Table VII shows the probability of the total FSP system mass exceeding various system masses for both the 40 kWe Gas-Cooled Brayton system and HP-Stirling system.

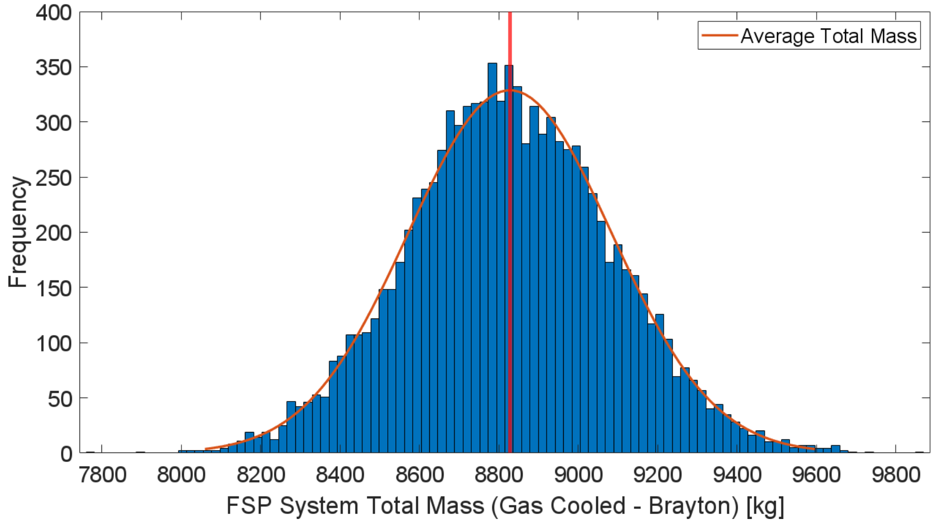

Figure 2.—FSP system total mass distribution for the 40 kWe Gas Cooled Brayton GRD system.

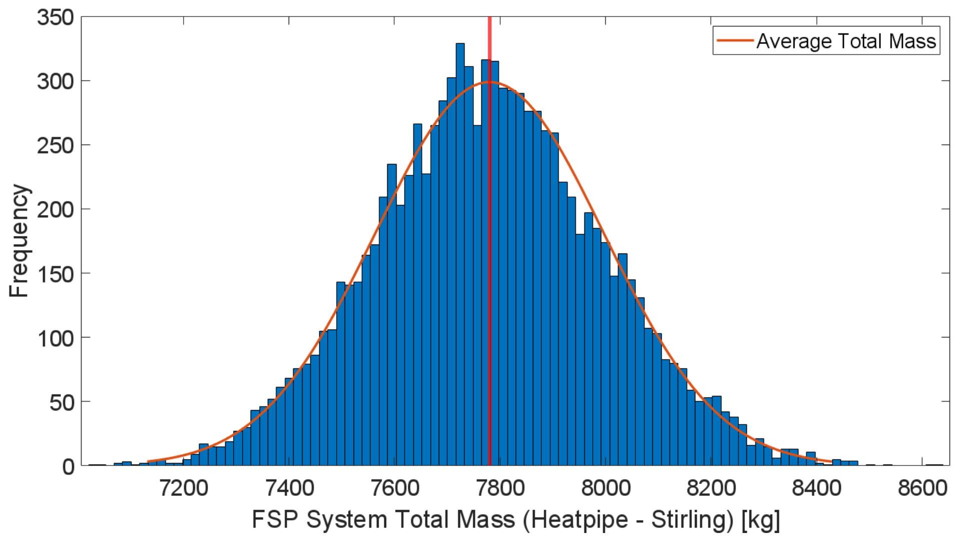

Figure 3.—FSP system total mass distribution for the 40 kWe Heatpipe Stirling GRD system.

TABLE VII.—PROBABILITY OF THE 40 kWe GRD FSP TOTAL SYSTEM MASS EXCEEDING A SPECIFIED MASS

Probability	40 kWe GC-Brayton	40 kWe HP-Stirling
$P(m_s > \mu)$	50.1%	50.4%
$P(m_s > \mu + 150\text{ kg})$	28.0%	25.4%

The code used to generate these results can be made available upon request.

It is important to note that the results shown in Table VII are not intended to be used for decision making. The goal of this section was to demonstrate a framework for propagating uncertainty and developing probabilistic models for FSP mass estimations, which may be useful for future decision-making work for lander/launch vehicles that can support an FSP system.

4.0 Conclusions

This report introduces a preliminary framework that quantifies and propagates the uncertainty of FSP mass estimates produced using the *EZ FSP Sizer* tool. This effort can augment the capabilities of the *EZ FSP Sizer tool* and help lay the foundation for future decision-making efforts that may benefit from uncertainty quantification.

To do so, the TRLs and AD^2 values for each FSP subsystem published in the 2024 FSP Technology Maturation Plan were used to generate a metric γ that is a proxy for mass growth margin. Higher TRL and lower AD^2 corresponds to lower γ and lower TRL and higher AD^2 corresponds to higher γ. A Beta probability distribution was used to represent the mass growth margin of each subsystem. The γ metric and the α shape parameter of the Beta distributions were parameters used to shape the 'flatness' and 'skewness' of the distribution. The higher the γ, the flatter and left skewed the distribution becomes, which is heuristically consistent with what is expected of systems with low TRL and high AD^2. The mass growth margin probability distribution function for each FSP subsystem was sampled 10,000 times and the average total mass and standard deviation of the FSP system was calculated using the Government Reference Design for a 40 kWe Gas Cooled Brayton and Heat pipe Stirling system. Total mass estimate results, which include uncertainty margins, indicated that the total FSP mass estimates calculated using the outlined method exceeds that provided by *EZ FSP Sizer*.

Since the γ and α parameters primarily govern the shape of the probability density functions, a sensitivity analysis was performed to quantify the impacts of variable TRL and AD^2 values (leading to a variation in γ) and a variable a shape parameter. Results showed that total FSP mass is most sensitive to the γ value of the shield followed by the reactor core, power conversion, heat rejection, user interface pallet, PMAD. Results also indicated that higher a result in lower standard deviation while lower α result in higher standard deviation. This demonstrates how uncertainty quantification inherently involves a level of subjectivity, as the specification of error bounds is an attempt at quantifying engineering judgement. Nonetheless, incorporating error bounds into decision-making is vital, as it provides insight into the implications and risks associated with the mass estimates deviating from reality. This analysis also highlights the necessity of developing FSP hardware to drive down FSP mass estimate uncertainties through empirical validation.

Another outcome of the uncertainty quantification process was demonstrating the propagation of mass uncertainty of each FSP subsystem to generate a probabilistic model for FSP mass estimates. This enables the estimation of the likelihood that the total mass of the FSP system may fall within a specified mass range, providing a framework that can support informed decision-making during mission planning.

5.0 Further Work

This section summarizes the identified areas of further work that can be addressed in subsequent studies.

5.1 Address Assumptions

Addressing the underlying assumptions listed in Table III is essential to improving the credibility and legitimacy of the uncertainty quantification process. The assumptions primarily reflect the methodological choices made by the author, which inherently involve a degree of subjectivity. While impossible to eliminate subjectivity from uncertainty quantification, it can be mitigated through rigorous historical data collection and by comparing results across multiple uncertainty quantification approaches. For instance, historical data of the mass growth of previously developed FSP subsystems (or analogous systems such as that reported in Ref. 7) across the TRL stages can be used to shape the mass growth margin probability density function of each subsystem through Bayesian inference. The γ metric can also be modified to reflect the minimum TRL and maximum AD^2 component of the subsystem for a conservative mass growth margin. The rationale for this modification is if a particular component does not perform as intended, the entire subsystem will be inoperable.

5.2 Cost, Risk, and Time (schedule) Uncertainty Quantification

In addition to quantifying the uncertainty in FSP mass, a similar analysis, rooted in TRL and AD^2 values, can be performed for FSP cost, risk posture, and time (schedule). These metrics are critical to the project and can assist with making informed strategic decisions, resource allocation, and risk management.

5.3 Confidence Interval Calculations

The probabilistic model for FSP mass estimates completed in Section 3.4 can be built upon through performing confidence interval calculations. Confidence intervals can express how much trust can be placed on the mass estimates, further aiding future decision making and risk analysis.

5.4 TRL and AD^2 Projection

TRL and AD^2 values will improve with technology development efforts. Projecting and capturing future TRL and AD^2 values, using methods such as the ATRA (Advanced Technology Roadmap Architecture) framework (Ref. 8), and incorporating them in the uncertainty analysis can be beneficial to establish timelines for development, integration, and deployment.

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